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Procedia Engineering 62 (2013) 769 – 777

Procedia Engineering

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The 9th Asia-Oceania Symposium on Fire Science and Technology

On determining density and specific heat of New Zealand medium density fibreboard

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Abstract

To model the burning behaviour of New Zealand medium density fibreboard (MDF), thermal physical properties of density and specific heat were experimentally investigated. An empirical equation is proposed to predict the vertical density profile along the MDF panel thickness. The model focuses on commercial MDF species with vertical density profiles that in general can be reproduced by a second order conic curve. The model predicted density profiles match the experimental data well and in general give better predictions to the core densities than to the peaks, which might partly because the hot pressing process has caused more complicated effects at the surface than at the core. The specific heat of MDF is measured experimentally using Differential Scanning Calorimetry (DSC). A simplified equation is developed based on the experimental outcome, which is found to be different from the models in the literature.

Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology

Keywords: MDF; Vertical density profile; Modelling; Thermal property; Specific heat

Nomenclature

A	added specific heat of MDF due to wood-water bond (J/kg/K)
c_p	specific heat of MDF (J/kg/K)
D_M	mean density (kg/m^3)
D_C	core density (kg/m^3)
D_X	density at certain thickness (g/cm^3 or kg/m^3)
D_P	peak density (kg/m^3)
L	depth measured from either surface (m)
L_0	thickness of MDF panel (m)
MC	moisture content
T	temperature of MDF
X	nominal depth
Greek symbols	
ρ	MDF density (kg/m^3)

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Selection and peer-review under responsibility of the Asian-Oceania Association of Fire Science and Technology
doi:10.1016/j.proeng.2013.08.124

1. Introduction

Medium Density Fibreboard (MDF) has been widely used in the construction industry as its features make it an excellent product for applications which require consistent performance, stability and fine finish. The production of MDF as well as High Density Fibreboard (HDF) has reached 12 million m^3 in Europe since 2005 [1] and four MDF plants have been established in New Zealand with a total production capacity of close to one million m^3 per year [2]. However MDF would be an important heat and toxic species contributor to the environment during fires. Therefore understanding its properties with regard to the burning behavior is critical to the fire engineering strategies in buildings.

Density is one of the important and fundamental properties for wood products due to its predominant effects on both mechanical [3] and thermal properties. In reality, a robust MDF should have a unbalance density profile along the panel thickness, so called vertical density profile (VDP), which is mainly formed from the hot-pressing process applied on the panel surfaces during the hot pressing process [2, 4]. In general, the surface density is considerably higher than the core density whereas the core is relatively more homogenous than the other parts of the panel [4, 5]. Usually a 5 MPa pressure is applied by a hot platen with a temperature up to 200 ºC on the fibre mats. The heat will be transferred from the surface into the cooler core through conduction and convection along with the moisture vapour migration. In commercial plant the pressure could go up to 7 MPa. Once the panel reaches its target thickness, the press closing stops meanwhile the majority of the VDP establishes other than some slightly changes due to the mat elastoplasticity and moisture migration between layers [6]. In other words, the VDP mainly develops at the press closing stage. The development of VDP due to the hot pressing process has been investigated by many researchers with several theoretical and mathematical models developed [7-12]. These developed models generally use the manufacturing conditions to predict the VDP. Among them Wang and Winistorfer [12] proposed a five stages model to describe the developing process of VDP, which has been widely accepted as a base of modelling the effect of hot pressing on densities profiles. However for most of the commercial MDF users such as the structure and fire engineers, it is hard to know the exact detail of the manufacturing process therefore it is unlikely for them to accurately predict the panel behaviour due to the absence of density profile in various projects. Usually engineers will be more concerning about the final VDP instead of its developing process in order to model it in practical. Some practicing work has been carried out using a uniform density profile [13], which leads to less reliable outcomes as the effect of density variation inside of the panel has been definitely ignored.

There is not much direct research on the specific heat of MDF whereas for recent modelling purpose, researchers have either used the value of moist wood [14, 15] or particleboard [2, 16] as a representative. It might be reasonable due to the fact that MDF is one of the wood based products. However, measuring the specific heat experimentally would lead to more confidence in modelling as well as filling the gap in the literature. In this case, differential scanning calorimetry (DSC), which has been regarded as an effective way of measuring specific heats of different materials [17, 18], will be used as a tool for determining the specific heat of MDF.

2. Mathematical model of determining VDP

A density gradient will develop during the manufacturing process due to the high temperature and pressure. This gradient leads to a vertical density profile along the MDF panel thickness, which has been recognized as a critical parameter correlated to physical properties of the MDF panel [19]. As a result, MDF is actually a highly inhomogeneous material whose properties will be a lot more complicated than the homogenous materials such as PMMA. According to Wang's five stages theory [12], the VDP starts developing with a uniform density along the thickness and builds up a higher surface and lower core density pattern as the pressure at the surface causes a compression nearby. The compression will travel towards the core due to the spring effect of the fibre mat and end up increasing the core density. As the compression at the surface is stronger than that at the core, the surface density is usually higher. However in reality, the peak density does not locate exactly at the panel surface. Instead, it normally occurs at an inner surface layer that is close to the panel boundaries. This is mainly because the thermal softening effect in the surface layer can partially be offset by the hardening effect of rapid moisture loss [6], which leads to a slightly lower density at the surface compared to the peak. However since the density peak is normally near the surface, it could be regarded as the representative of the surface density and the variation at the surface region can be ignored in order to simply the problem. To determine the VDP of MDF, Wu and Xiong [20] proposed a simple one line equation by correlating the local density with the depth inside of the panel, which is

$$D_X = 1.0258 - 1.3917X + 1.3205X^2 \tag{1}$$

where X is the nominal depth calculated as the ratio of the position depth and the total thickness. The model can predict the shape of the vertical density profile through the panel thickness however its feasibility is limited by the fact that Wu and

Xiong have only taken one type of MDF into account. On the other hand, by using the experimental results covering a wide range of different MDFs, Gupta et al. [19] proposed an equation to determine the peak density of MDF by using the mean density, which is

$$D_P = 0.5295 D_M + 513.65 \tag{2}$$

where D_P and D_M is the peak and mean densities. Gupta's model has considered the density variation of different MDFs as well as taking the moisture content into account therefore it suits a wider range of MDF species. The down side of Equation (2) is it can not predict the vertical density profile along the panel thickness. Therefore combining Equations (1) and (2) might overcome their respective limitations. However Gupta has only used 10 to 13.5 mm thick panels for developing the equation whereas the actual MDF thickness could go up to 30 mm. Trial calculation has shown that Equation (2) excessively under-predicted the peak density in some cases where MDF has a larger thickness. It should be noted that Gupta has used the mean values to determine the peak densities but instead of using mean density derived from the laser density scanner, engineers tend to use the bulk (average) density as it is relatively easy to obtain. The bulk density is usually slightly higher than the mean density due to the fact that the laser density scanner under-predicts the material density near the surface as the radiation beam can not been fully blocked by the regarding material when the sample just starts travelling across the radiation beam. This effect can actually be overcome by increasing the scanning resolution. A high resolution profile is easy to be identified as it will normally present relatively high density values near the surface [6, 21]. In terms of the calculation, the difference between the bulk and mean densities is generally less than 5%. Therefore it is reasonable to use the mean density to represent the bulk density. Furthermore a correlation of peak density as a function of mean density can be developed using the experimental data in the literature. In this case, two sets of experiments conducted by Gupta and Wang et al. [2, 4] are used to develop the correlation of the mean and peak densities. As shown in Fig. 1, since the first term at the right hand side of Equation (1) is basically a representative of the peak (surface) density, substituting it with the fitting result in Fig. 1 gives

$$D_X = \frac{(0.9691 D_M + 280.45)}{1000} - 1.3917X + 1.3205X^2 = 0.9691 D_M - 1391.7X + 1320.5X^2 + 280.45 \tag{3}$$

where D_M is the mean density of MDF. It should be noted that the bottom density of MDF would be slightly less than the top density however the difference is quite insignificant in terms of the literature records [2, 4]. Meanwhile it is hard for a

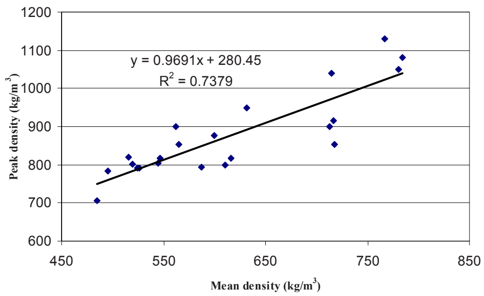


Fig. 1. Correlation of mean and peak density (using experiments listed in Table 2 excluding L-1 and L-2).

general customer to identify exactly the top and bottom of a panel. Therefore it is reasonable to assume a "symmetric density profile", which leads to a revision of the nominal depth, X, in Equation (3) as such

$$X = \frac{\frac{L_0}{2} - \left| L - \frac{L_0}{2} \right|}{L_0} \tag{4}$$

where L_0 is the thickness of the panel and L is the depth measured from either surface. By using Equations (3) and (4), the vertical density profile can be determined. The vertical density profiles measured in the experiments listed in Table 1 are used to validate the model. It is should be noted that the MDF samples used in Gupta's experiments were made complying with the commercial pressing cycle in New Zealand with a total pressing time of 350 s whereas different pressing times from 20 s to 135 s leading to similar results had been used by Wang. Other than the data in the literature, two sorts of commercial MDFs were also tested in current study. The MDF panels were bought from a local manufacturer and they are 25 and 18 mm thick as shown in Fig. 2. Density at various thicknesses were measured and compared to the model predictions to further validate Equations (3) and (4).

Table 1. Selected experiments for model validation

Source	Label	Thickness (mm)	Target density ($kg\ m^{-3}$)	Mean density ($kg\ m^{-3}$)	Mean density determining method
	G-1	10		713	In the literature
	G-2	12		610	In the literature
	G-3	13.5		495	In the literature
Gupta	G-4	19	N/A	715	Calculated using VDP
	G-5	19		632	Calculated using VDP
	G-6	19		562	Calculated using VDP
	G-7	24		520	Calculated using VDP
	W-A	15		767	Calculated using VDP
Wang	W-B	15	760	784	Calculated using VDP
	W-F	15		780	Calculated using VDP
Li	L-1	25	N/A	733	Measured
	L-2	18		727	Measured

(a) (b)

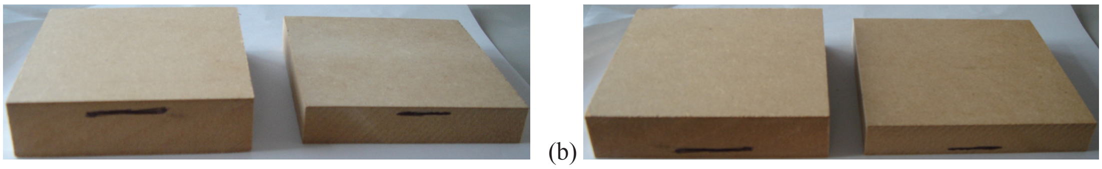


Fig. 2. Photo of two used MDFs (a) Surface 1 (b) Surface 2.

3. Validation of mathematical model

3.1. Comparison of vertical density profile

As shown in Fig. 3, the model generally gives pretty good predictions regarding the overall magnitude and shape of the profiles, especially to the cases with relatively small thickness (less than 15 mm). When the panel thickness exceeds 15 mm, the model seems to slightly over-predict the core density. The biggest discrepancy between the experiments and model predictions at core occurs in Wang's cases where the difference is less than 5%. On the other hand, the prediction at the surface region for the density peak shows scatter outcomes where it might either over-predict the peak density when the thickness is less than 15 mm or under-predict it when the thickness is larger than 15 mm. The largest discrepancy could be up to 10% in Case W-A. It should be noted that in this case the peak densities from the literature have been used to represent the surface density of MDF. As a result, in such cases where the peak density location is relatively far from the surface, it might lead to a relatively large error between the model prediction and the actual density. As the peak values are generally obtained within 1 mm away from the surface in the experiments shown in Fig. 3, it can be reasonably expected that the peak density has given a reasonable representative to the surface density, which is usually the case in commercial MDF. The profiles would have matched better if the predicted peak density was moved to the depth at which the experimental peak is locating. However it is hard for a user to determine where the density peak is. Therefore leaving the model as it is will be more appropriate to its practical uses.

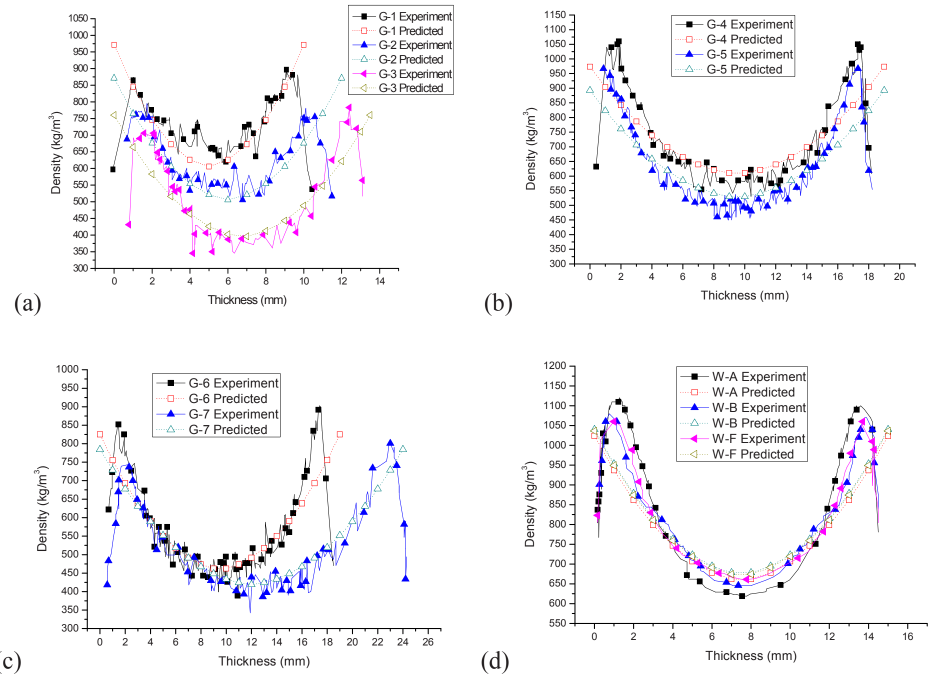


Fig. 3. Comparison of experimental and predicted vertical density profiles. (a) G-1 to G-3 (b) G-4 and G-5 (c) G-6 and G-7 (d) W-A, B and F.

It is hard to identify the top and bottom surfaces of the two MDFs measured in current study given the manufacturer has not provided any regarding information. Comparison of the densities of different surfaces gives little difference therefore the MDF panels is reasonably assumed to be symmetric with regard to the vertical density and only half of the density profile is presented. As shown in Fig. 4, the comparison shows that the model prediction agrees well with the experimental result in Case L-2 whereas in Case L-1 the densities are slightly over-predicted. Both core densities are slightly over-predicted by the model but the discrepancy is less than 30 kg/m3 which is not noticeable. In order to measure the density, small samples at various locations were cut manually as 20 mm square and sanded as 1.0 ~ 1.5 mm thick. The samples were cut at a 3 mm spacing, which leads to 5 samples in Case L-1 and 4 samples in L-2. In this case, the average value along the sample thickness has been used to represent the density at the cutting point. One of the disadvantages out of this is that it is only capable of measuring the average density along a certain thickness, which could be one of the reasons leading to the over-predictions. As a result, it can not identify the detail inside of the sample such as the difference between the surface and peak densities. As a result, it can be seen in Fig. 4 that the surface (peak) density is basically higher than the rest parts of the panel.

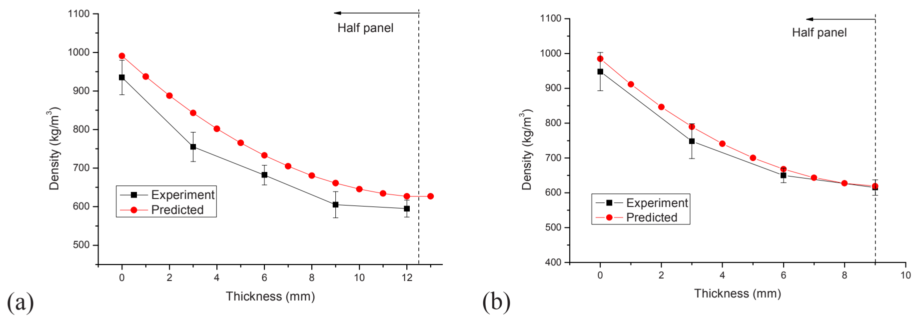


Fig. 4. Vertical density profile of two MDFs. (a) L-1 (25 mm) (b) L-2 (18 mm).

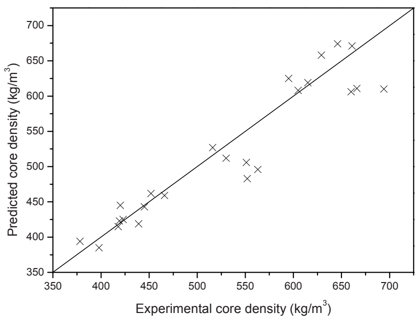
3.2. Core density

In terms of the overall results presented in both Figs. 3 and 4, the predictions at the cores generally match the experiments better than those at the surfaces. By using Equation (3) with setting X as 0.5, the core density can be determined as

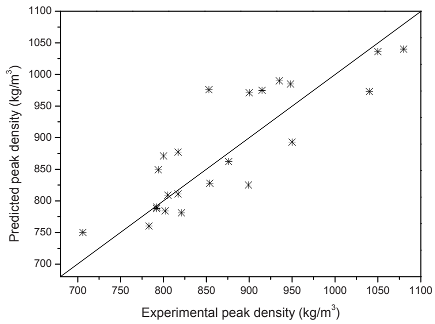
$$D_C = 0.9691 D_M - 85.28 \tag{5}$$

where D_C is the core density. Without going into the detail of density profile, Gupta [2] provided a set of experiment data with the mean, peak and core densities recorded. Table 2 recorded the experiments as well as those listed in Table 1. It was noted that these experiments have been used to develop Equation (3). As shown in Table 2, the core densities calculated using Equation (5) have been presented. Comparison between the experimental and calculated results is plotted in Fig. 5(a) in which it can be seen that Equation (5) performs fairly well in predicting the core densities of MDF other than slightly under-predicting it in some case when the core density is higher than 500 kg/m^3. In general, the core densities are within a range of 350 to 700 kg/m^3. As shown in Fig. 5(a), the error is pretty acceptable as the data are scatter near the equal line and the overall discrepancy in general is less than 10% except for some cases where the error could go up to 12%.

Figure 5(b) plots the results of peak densities. Compared to the core density, the predictions of peak densities using current model are less comparable, which is possibly caused by the fact that the impact of hot pressing at the surface is stronger compared to the core due to the direct contact with the platen. Therefore density at the core will be more linearly correlated to the mean density compared to the one at the surface. The model either over-predicts or under-predicts the experimental result with discrepancies being larger than those of the core densities in terms of the overall pattern. However the errors are generally less than 100 kg/m^3 and 12% other than only one case where the difference of experiment and prediction is 123 kg/m^3 leading to the highest error of 15%. The peak densities are generally within the range of 700 to 1100 kg/m^3.



(a)



(b)

Fig. 5. Comparison of measured and predicted core density and peak density. (a) Core density (b) Peak density.

Table 2. Summary of experimental and model calculated densities

Label	Mean density (kg m^{-3})	Experimental core density (kg m^{-3})	Predicted core density (kg m^{-3})	Experimental peak density (kg m^{-3})	Predicted peak density (kg m^{-3})	Difference of peak and core densities (kg m^{-3})
N/A	485	398	385	706	750	308
N/A	516	418	415	821	781	403
N/A	524	419	423	792	788	373
N/A	526	423	425	792	790	369
N/A	545	445	443	805	809	360
N/A	547	420	445	817	811	397
N/A	565	452	462	854	828	402

N/A	587	552	483	794	849	242
N/A	600	563	496	876	862	313
N/A	616	530	512	817	877	287
N/A	717	694	610	915	975	221
N/A	718	666	611	853	976	187
G-1	713	660	606	900	971	240
G-2	610	551	506	800	871	249
G-3	495	378	394	783	760	405
G-4	715	605	608	1040	973	435
G-5	632	516	527	950	893	434
G-6	562	466	459	899	825	433
G-7	520	439	419	802	784	363
W-A	767	629	658	1130	1025	511
W-B	784	646	674	1080	1040	434
W-F	780	661	671	1050	1036	389
Li-1	733	595	625	935 (surface)	990	340
Li-2	727	615	619	948 (surface)	985	333

4. Specific heat

Several models have been developed to determine the specific heat for wood and wood products. By adding the specific heat of moisture into the specific heat of dry wood using the simple mixture method, Siau [22] proposed an equation for moist wood:

$$c_p = 4180\frac{0.268+0.0011T+MC}{1+MC} = \frac{1120.24+4.598T+4180MC}{1+MC} \tag{6}$$

where T is the temperature in °C and MC is the moisture content. Haselein [23] gives a similar expression regarding the specific heat of particleboard specifically, which is:

$$c_p = \frac{1131+4.19T+4190MC}{1+MC} \tag{7}$$

Equations (6) and (7) lead to similar results in which the specific heats of dry wood product are to be 1300 J/kg/K at ambient temperature. TenWolde et al. [24] conducted a set of comparison using the experimental results and the existing equations in the literature. He suggested that one of the developed models gave the most reasonable agreement to the experiment data, which is:

$$c_p(dry) = 3.867(T+273.15)+103.1 \tag{8}$$

$$c_p(wet) = \frac{c_p(dry)+4190MC}{1+MC} + A \tag{9}$$

$$A = \left[23.55(T+273.15) - 1320MC - 6191\right]MC \tag{10}$$

The model involving Equations (8) ~ (10) has also taken the bond-water effect into account by adding a correcting term A into the calculation compared to Equations (6) and (7). The model can be used on solid wood as well as fibreboard and it can be calculated that the specific heat at ambient temperature is around 1300 J/kg/K which is similar to the values given by the other two models.

A SDT Q600 thermal analyzer has been applied to experimentally measure the specific heat of MDF. The experimental process complies with ASTM standard 1296 [25] in which the heating rate is required to be specified as 20 K/min. However, since it takes some time for the interior environment to reach thermal stabilization a 20 K/min heating rate can only measure the specific heat at the temperatures higher than 70 ºC. Therefore in order to expend the temperature range, a 5 K/min heating rate is also employed in the experiments. The highest temperature in the experiments has been set as 180 ºC as in general the MDF will start decomposing once the temperature reaches 200 ºC. Ideally material at the surface and the center should be identical, which lead to the same specific heat although the densities at various locations are different. To evaluate the difference of different locations as well as accounting for the experimental uncertainties, tests have been conducted at both the surface and the center of the panel for the two MDF species. The experimental results have been plotted in Fig. 6 with the calculated values by using Equations (6-8). As shown in Fig. 6, the measuring temperature range at 5 K/min heating rate is 40 ~ 110 ºC and at 20 K/min it is 70 ~ 180 ºC. As the sensitivity of the facility drops down once the heating rate is reduced to 5 K/min, the specific heat curve becomes less smooth than the one at 20 K/min. However the trend is still noticeable while the data at 5 and 20 K/min overlap at 70 ~ 110 ºC, which justifies the consistence of the experiments. The measured specific heats of the 25 mm sample are slightly higher than the ones of the 18 mm sample but the difference is less than 30 J/kg/K which in general could be ignored or regarded as the experimental uncertainty. Therefore it is a reasonable assumption that the specific heats of different species at different locations are all the same. Linearly fitting the experimental results gives:

$$c_p(dry) = 2.5T + 1080 \tag{11}$$

Specific heats calculated by Equation (11) are also plotted in Fig. 6. It can be seen in Fig. 6 that predictions made by the different models in the literature are similar with a lowest cp of 1200 J/kg/K at 10 ºC and a highest cp of 1900 J/kg/K at 180 ºC whereas the experiment leads to similar cp of 1100 J/kg/K at 10 ºC and a lower cp of 1600 J/kg/K at 180 ºC. Errors of model predictions and experiment results are within 9 ~ 19 % at the temperature range of 10 ~ 180 ºC. It should be noted that current experiments can only handle dry MDF samples as the moisture vaporization will affect the measurements which leads to difficulties of determining the specific heat of sample mixed with moisture. In fact, each test will be repeated twice during the experiments where the first run is used to dry out the samples and the sample weight in the second run will be monitored to make sure there is not moisture left.

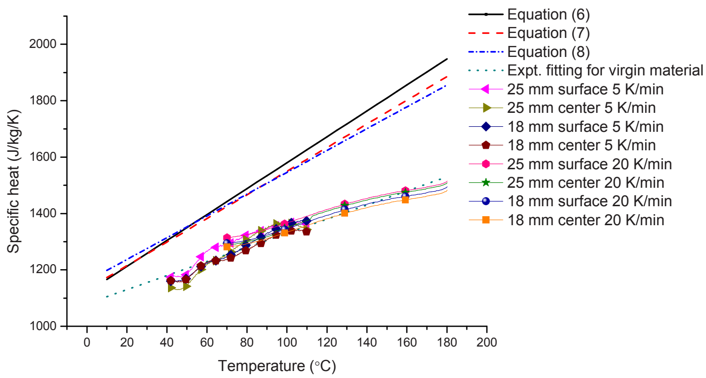


Fig. 6. Comparison of measured and predicted specific heats.

5. Conclusions

In order to model the burning behaviour of MDF pyrolysis in fires, the thermal physical properties of the material must be provided for predicting the heat transfer process penetrating a MDF panel perpendicularly, which is regarded as a typical heat transfer process for MDF panels in fires. Experiments were carried out to determine the regarding thermal physical properties. It is found that MDF species present vertical density profiles with a surface density being about two times denser than the center density. An empirical model is then developed to predict the vertical density profile of MDF based on several sets of experimental data. The validation using several sets of experimental justified that the simplified equation predicts the vertical density profiles of MDF very well therefore it can be used to mimic the density profiles of numerical modeling. The specific heat of MDF is determined by DSC and compared to the literature reports for other wood species. The measurements show that the specific heat of MDF is lower than the literature values which have been widely used for general wood materials and products such as particle board. Future researches should be conducted to investigate the thermal physical properties of charred MDF.

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